Development of a Low-cost, Portable Surrogate - The 3-Rib Chest Structure

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Introduction

Law enforcement and military agencies are increasingly called upon to neutralize potentially life-threatening situations without employing lethal force. As a result, these agencies have experimented with and deployed to varying degrees a number of presumably nonlethal weapons. Resources have been dedicated to advancing nonlethal technology, particularly in the last decade. Manufacturers have increased the available nonlethal arsenal in an effort to provide a spectrum of implements suited to the continuum of scenarios encountered by authorities. Whether confronted with a single distraught individual threatening to take his/her own life, or a large rioting crowd posing an imminent threat to the property and lives of others, authorities are expected to resolve the conflict without imposing excessive force so that a fatal outcome may be averted. However, even limited experience with nonlethal technology has demonstrated that fatalities may still occur (1). As such, a means to evaluate the risk and extent of injury associated with a typical use of nonlethal force is necessary. However, no standard test method currently exists by which to evaluate the probability of a lethal or nonlethal outcome.

Injury Criteria

The automotive industry has extensively explored the effects of blunt trauma (2) in an effort to reduce injuries associated with vehicular accidents. As the research of blunt thoracic impacts has evolved, so have the various injury tolerance criteria associated with these impacts. The first frontal impact tests and standards relied upon a criterion based purely on spinal acceleration. This criterion, labeled the Acceleration Criteria, was solely based on the peak acceleration and stated that it should not exceed 60 g's for longer than a 3 ms period (3). Although the measurement of spinal acceleration is a good measurement of whole body impacts, it was found to be an inaccurate assessment of the deformation of the thoracic cavity. It is primarily useful in determining skeletal injury, therefore, soft tissue injury data is not available with this criterion. However, the criterion is widely used in civilian and military vehicle crash safety assessment.

Studies related to energy-absorbing steering columns conducted by Patrick et al. (4) depended upon the level of force as the sole criterion for injury. Cadavers were used to impact padded load cells in order to determine the forces experienced by the body region of interest. While the Force Criterion contributed to the implementation of this new safety device, it did not accurately characterize all mechanisms of injury associated with blunt thoracic trauma. This was due to the variable nature of the inertial, elastic, and viscous components of the human body on the reaction force developed.

Based on an analysis of cadaver testing, Kroell identified maximum chest compression as an indicator of severity of chest injury (5, 6). Kroell demonstrated that rib fractures occurred when impact velocities of 5-7 m/s induced thorax compression of greater than 20 percent. When the compression reached 40 percent, multiple rib fractures occurred in the cadavers tested. This type of injury would be clinically manifested as flail chest which is considered a life-threatening injury. The Compression

Criteria is a valid injury indicator only if the chest is treated as a rigid body. However, the vital organs within the chest cavity necessitate consideration of the mechanism of soft tissue injuries to provide an accurate indication of thoracic injury.

When examining soft tissue injuries there has been a relationship noted not only to the amount of chest compression but also to the rate of compression (7). In experiments with a constant magnitude of compression, an increase in the velocity of compression led to an increase in the severity of injury. While the Compression Criteria captures the contribution of the magnitude of compression to thoracic injury, it does not consider the rate of compression and therefore has a limited range of validity.

The relationship between compression and velocity of compression was further validated as a factor in the causation of blunt thoracic injury by Kroell et al. (8). Viano and Lau (9) demonstrated that the injury tolerance of soft tissues was related to a viscous response. Within their testing regimen, impacts were conducted on anesthetized rabbits with impact velocities ranging from 5-22 m/s and maximum thoracic compressions of 4-55 percent. The amount of chest compression (C) is defined as the displacement of the chest in relationship to the spine normalized by the initial thickness of the thorax. This analysis demonstrated that both the compression (C) and the rate a which it occurred (V) should be considered to accurately predict the risk of injury.

These two parameters were brought together in the form of the Viscous Criterion or VC. Logist analysis indicated that the combination of velocity of compression and amount of compression (VC) had a higher predictive ability of injury than either velocity (V) or amount of compression (C) alone. Viano and Lau (15) further validated the Viscous Criterion (VC) with a reanalysis of existing cadaver data. Again it was demonstrated that the maximum Viscous response was highly correlated to the risk of severe soft tissue, internal organ, and functional injury. A tolerance level of a VC max value of 1.00 m/s was established which correlated to a 25% probability of injury for frontal chest impacts. Further testing demonstrated the ability of VC max to predict the probability of heart rupture (11) and correlates with cardiac arrhythmia. Severe liver lacerations were also found to be predicted by VC max (12).

The range of validity of VC max has also been delineated (10, 12). For impacts resulting in velocity of chest deformation between 3 and 30 m/s, VC max is able to predict the risk of injury. When the deformation velocity is below 3 m/s, the injury becomes primarily due to the crushing of tissue such that the Compression Criteria is a more suitable indicator. When the velocity of deformation is above 30 m/s, the injury is predominantly caused by the velocity component. At these higher velocities the injuries are due to a blast mechanism (13).

Biomechanical Surrogates

Even though the human injury tolerance has been established for a given impact and suitable criteria have been developed, each specific impact scenario should be assessed to determine its injury potential. In an effort to reduce the need for extensive animal or cadaver testing, the development

of biomechanical surrogates has been pursued. Once designed and validated, surrogates provide a means for obtaining large amounts of data without the utilization of live animals or cadavers. The first mechanical surrogates were developed by the military to test ejection seats in the late 1960's (14). The need for more accurate and precise data in vehicular crash analyses resulted in a more sophisticated family of surrogates being developed by the automotive industry.

The first family of biomechanical surrogates that most accurately demonstrated human-like chest responses for frontal impacts was the Hybrid III (15). The Hybrid III family of surrogates includes: 5th percentile female, 50th percentile male, 95th percentile male, 6 month old, 3 year old, and 6 year old. Each of these surrogates correlates with the anthropomorphic grouping it represents in relation to its external dimensions and compliance of internal structures. The need for assessment of lateral impacts led to the development of side impact surrogates such as the EuroSid and BIOSid (16).

The validation of biomechanical surrogates has primarily been based on data collected with mechanical impacts to cadavers (17). From these impacts, response corridors were generated:

Curves identified as follows:

Curve No - Cadaver No/Age/Ht(in) x Mass (lb) /Striker Mass (lb) x Vel (mph)

1 — 53FM/75/68.5 x 170/50.6 x 11.7   6 — 63FM/53/72 x 194/50.7 x 15.5 (rigor)
2 — 45FM/64/71.5 x 141/50.7 x 11.3   7 — 32FM/75/67.5 x 120/50.4 x 22.2
3 — 60FM/66/71 x 175/50.6 x 9.7   8 — 31FM/51/72 x 165/50.8 x 22.8
4 — 42FM/61/72 x 120/50.4 x 10.9   9 — 24FM/65/72 x 180/50.4 x 21.8 (Ref [2])
5 — 64FM/72/64 x 139/50.7 x 15.5   10 — 37FM/48/70.5 x 163/50.4 x 22.0

\\\\\\\ — Corridor of seven tests @ 15.0-16.5 mph from Ref [2]
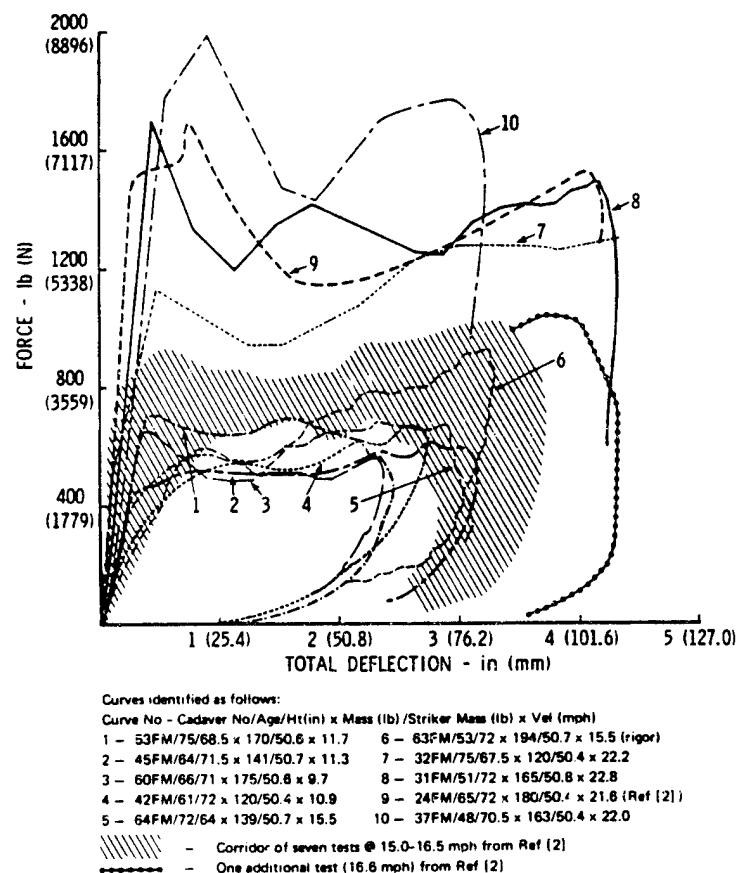•——• — One additional test (16.6 mph) from Ref [2]

Figure 1: Human response corridors established with high mass, low impact velocity impacts to cadavers. Kroell, C.K., Schneider, D.C. Nahum, A.M. Impact tolerance and response of the human thorax II. SAE 741187 18th Stapp Car Crash Conference, 1974.

These corridors help to establish the biofidelity of the surrogates. The corridors were established with those impact characteristics seen in vehicular collisions, or high mass, low velocity impacts. The velocities of impacts ranged between 5 - 9 m/s and the mass of the impactor varied from 50 - 85 kg. Pendulum impact tests, simulating similar conditions, were then performed on the HybridIII to demonstrate the correlation of its response to that of the cadavers.

Once validated, the surrogates allow an injury risk assessment to be conducted given a blunt impact. Sensors are placed within the surrogate to collect valuable mechanical data. Each of the Hybrid-III systems has a variety of accelerometers and a potentiometer strategically placed to obtain key information. To assess the injuries associated with chest impacts, chest displacement is measured over the time of the impact. From this measurement, VC max can be calculated.

Development of 3-Rib Chest Structure

Based on the advancements in the automotive industry, it would seem logical that the same approach could be taken to establish the risk of injury due to nonlethal munitions. However, the transition from the high mass, low velocity impacts typical in the automotive industry to the low mass, high velocity impacts characteristic of nonlethal projectiles must be critically evaluated and made with caution. The first step is to determine human tolerance criteria. Given that the most severe injuries are occurring with blunt frontal chest impacts, VC max appears to be the most suitable of the criteria developed to date. Because VC max has been validated for chest deformation rates up to 30 m/s, it would appear to be a viable criterion to test.

The next step is to elucidate the type of biomechanical surrogate to employ for the impacts. The HybridIII, since developed and validated for frontal impacts, appears to be the logical choice. However, preliminary testing with this device has revealed inadequacies related to the high velocity impacts of nonlethal projectiles. The sensors within the surrogate and the internal design of the thorax system do not provide the kind of repeatable response needed for these impacts.

When exploring other options, it was noted that the BIOSid ribs were a continuous structure and would provide an adequate loading surface. The Hybrid-III ribs come in two halves which are connected to a leather sternum that is not suitable for projectile impacts. The development of a transducer that could track higher velocities would also provide an option for more accurate tracking of the impact. By combining these two key elements into one structure, the 3 Rib Chest Structure (3-RCS) was created. Three BIOSid ribs were mounted to a spine box opposite the impact side. Damping material on the inside of the rib provided for viscous bending resistance and allowed for the dissipation of energy. Nylon supports were mounted to the sides of the spine box to prohibit gross upward and downward motion of the ribs.

The impact surface was created with a 15.5 cm high and 23 cm wide urethane bibb that tied the three ribs together on the impact side. A padding made of Ensolite7 approximately 5/8 inch thick covered the urethane plate. This padding was chosen for its response characteristics after testing of about 10 pads of different materials. The conductive-plastic position transducer was mounted to the interior

of the middle rib directly behind the urethane bibb so that device displacement could be measured and a VC max calculated.
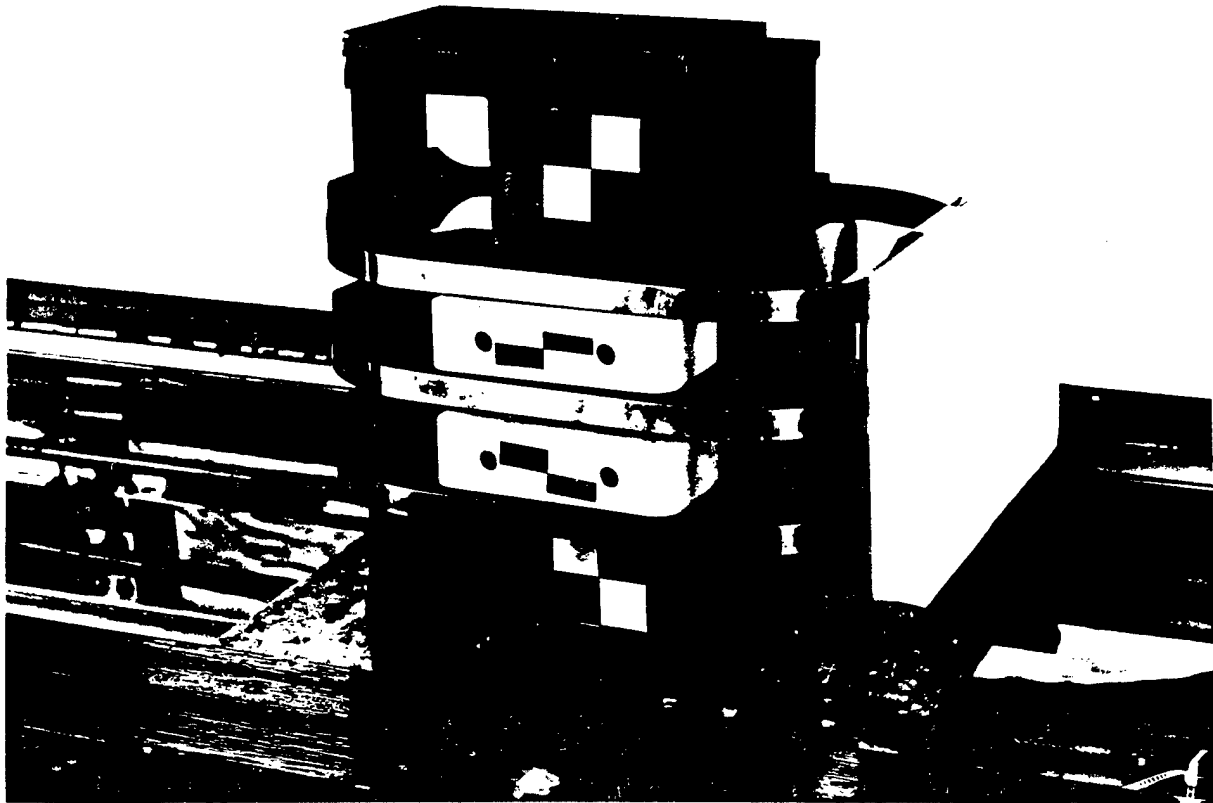

Figure 2: 3-Rib Chest Structure (3-RCS) developed from BIOSid ribs for low mass, high velocity impacts.

Preliminary testing was conducted on a variety of non-lethal munitions. Some general observations were made during testing. For all impacts, the location of shot placement is vital. Currently, the only transducer to record the amount of chest displacement is directly behind the middle rib. By virtue of this design, if one of the other ribs carries the majority of the load transfer, the transducer does not track an accurate amount of actual chest displacement. This is best seen on the high speed video where an impact to the upper or lower rib causes large displacements in the respective rib and minimal displacement in the middle rib. The establishment of the region of acceptance helps to compensate for this problem. However, potentially worthwhile data are lost.

Due to the high velocity at which the impacts occur, the transducer must be able to track higher velocity rib displacement than those seen in automotive impacts. From observing the video and comparing it to the measured displacement, it is noted that the recorded maximum displacement is not always accurate. This is especially true with the higher kinetic energy rounds where the transducer experiences a higher transfer of energy. This energy creates a large spike of noise in the output. By filtering the data the majority of this phenomenon is eliminated. However, not all of the noise can be filtered. Therefore, the guideline of a maximum velocity of $\leq 10m/s$ for acceptance was established based on the specifications of the transducer.

Another limitation is the transducer specifications and sensitivity of shot placement. If a tracking system could be identified that records higher velocities then this system could be placed on each rib. This would help to eliminate both of these limitations. However, the greatest limitation with this testing system is a lack of established biofidelity. A data set does not currently exist from which human response corridors can be established. The establishment of such a database will allow for a completion validation process to occur.

Conclusions

There is a need that exists in the law enforcement arena to be able to diffuse threatening situations without the use of lethal force. However, before this need is met, there is also a need to determine the lethality of the force employed. Without knowing the injury risk associated with the utilization of non-lethal technology, the deployment of this technology can potentially become a liability. The ability to test the nonlethal projectiles in a controlled environment allows for a thorough assessment to occur prior to utilization in the field. This allows for a higher level of protection for both the officer/agent utilizing the technology as well as the assailant. The validation of the 3-RCS against the human cadaver responses will provide a means for providing this protection. Once validated, virtually all types of nonlethal munitions can then be tested with the device and a percent risk of injury can be determined prior to the utilization of the munition in the field.

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